MILD HYPOXIA AND VISUAL PERFORMANCE

WITH NIGHT VISION GOGGLES

BY

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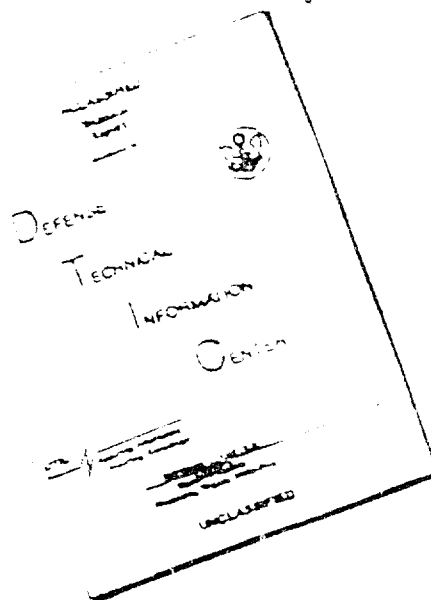
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ABSTRACT

MILD HYPOXIA AND VISUAL PERFORMANCE

WITH NIGHT VISION GOGGLES

BY

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Master of Arts in Psychology

New Mexico State University

Las Cruces, New Mexico, 1985

Dr. Stanley N. Roscoe, Chairman

Frequently a technological advancement is introduced in
military systems with benefits so great that little effort is
expended to optimize its use by human operators. Sometimes even
serious limitations are not investigated because the device adds
such obvious improvement to mission performance. This is the case
with the night vision goggle (NVG) image intensifiers currently
used by United States Army and Air Force Military Airlift Command
(MAC) rescue personnel. Although the goggles are normally used
when the human operator's visual capabilities are unimpaired, they
are also worn by mountain search team members and aviators. Limits

of use have not been established, nor do we have sufficient understanding of the effects of mild hypoxia on visual performance with NVGs to establish such limits objectively.

Pilots have frequently reported an apparent darkening of the visual field while flying at high altitude without supplemental oxygen, and subsequent exposure to oxygen resulted in marked increases in the b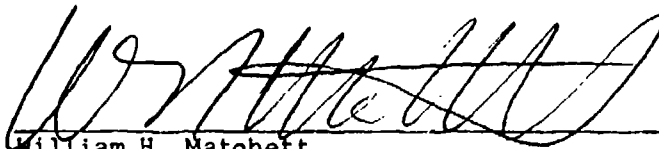rightness of lights. (Goldmann & Schubert, 1933). Likewise, at low light intensities visual acuity is greatly decreased during oxygen deprivation. (McFarland & Halperin, 1940). In contrast, at high light intensities, the effect of moderate oxygen deprivation on visual acuity is slight. Even though the NVGs amplify low night illumination, the interaction between amplified illumination and high altitude effects may prove to be important factors in visual performance.

The objective of this research was to investigate the effects of mild hypoxia on monocular visual performance with NVGs. This study revealed that mild oxygen deprivation significantly affects unaided square-wave grating visual acuity but does not significantly affect NVG-augmented performance. Large differences between visual sensitivities at different spatial frequencies were not differentially affected by mild hypoxia. Supplemental oxygen did significantly improve naked-eye but not NVG-augmented night resolution acuity up to an altitude of 13,000 feet (3,962 m) above sea level (ASL).

"Mild Hypoxia and Visual Performance with Night Vision Goggles,"

a thesis prepared by Leray Lyle Leber in partial fulfillment of

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        Communication

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Introduction

Night Vision Goggles

The AN/PVS-5 night vision goggle system (Figure 1) is a 1.9-pound, battery-operated, self-contained, head-mounted (helmet-mounted for aviators) binocular system that both intensifies and augments existing light. Photocathode optics using the P20 phosphor provide a grainy greenish tint to all viewed objects within their 40-degree field of view. Goggle spectral response of 360 to 900 nm (Figure 2) is more sensitive to infrared radiation than the normal human visual response of 400 to 700 nm (Jensen, 1981). An internal infrared-emitting diode provides supplementary illumination for close-range viewing when external light is not available. The binocular system has independently adjustable focus for each monocular lens, allowing focus between 15 inches (38.1 cm) and optical infinity.
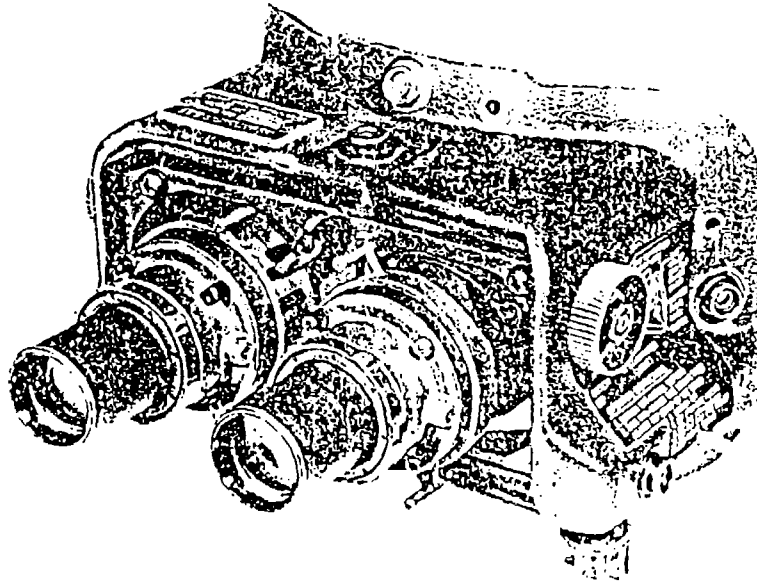
Figure 1. AN/PVS-5 night vision goggle system.

The goggles were originally designed to provide their wearers
with improved night vision for reading, performing manual tasks,
patrolling, medical aid, construction work, mobile equipment
operation, driving, walking, air support, and surveillance using
starlight and moonlight from the night sky. They provide unity
magnification, with viewing range approximately 150 m for man-size
targets and 350 m for vehicle-size targets. The NVGs require a
2.7 volt d.c. power supply, and the life of their single 3/4-inch
round battery is 12 hours. Their ambient temperature operating
limits allow use betw ~ -65 and 125 degrees Fahrenheit. Today,
the NVGs are routine,y worn by Army and MAC ground party searchers,
pilots, aircrew members, and scanners (searchers) aboard aircraft.

The NVGs incorporate variable gain light amplification and
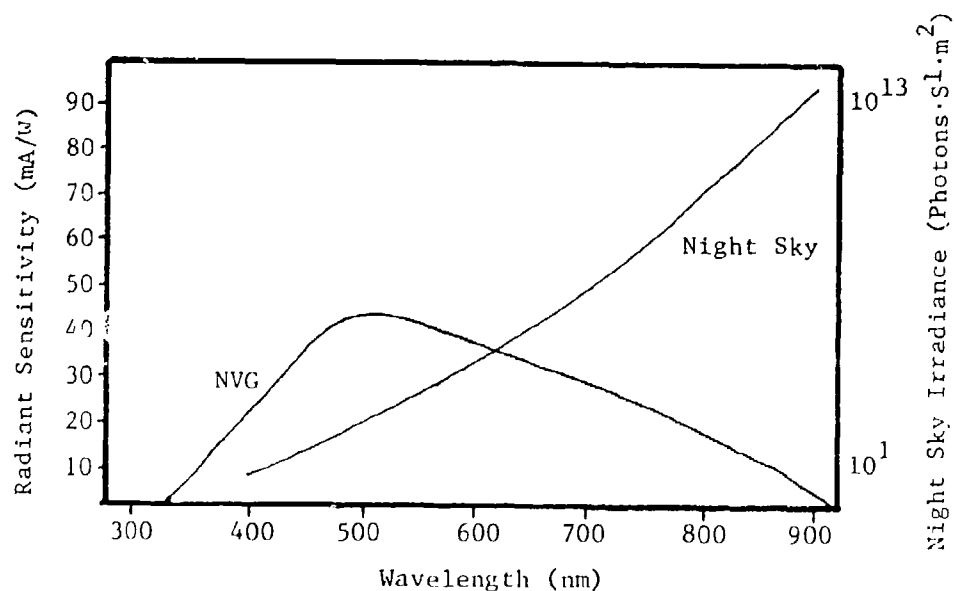
Figure 2. NVG sensitivity and night sky irradiance.

thereby affect the conditions under which an operator can perform visual tasks. For example, they transform scotopic conditions, an environment with ambient starlight illumination (10^{-4} cd/m^2), into comfortable-reading, mesopic conditions (1 cd/m^2). Thus, the NVGs change the retinal stimuluation from a state in which rods dominate visual detection and resolution to one in which b$\mathtt{\cdot}$ rods and cones contribute in visual performance. Although the NVGs offer a significant improvement over vision with the naked eye, the use of NVGs creates a different visual environment, one that may involve deleterious side effects.

Visual Performance

Spot detection threshold. The primary stimulus for vision is the absorption of light by retinal photoreceptors. Detection studies have shown that only a few quanta of light are needed for detection with scotopic or rod vision in ideal conditions (Bouman & van der Velden, 1947, plus an extensive bibliography by Davson, 1962). Sometimes there is a distinction made between search detection and threshold detection, the former entailing a local search task, whereas the latter refers to the presence of a stimulus in a fixed location made known to the observer prior to introduction.

Any surface or volume that emits radiant energy is a source. Every source has finite size, but when its size is small compared with its distance to the observer, it is called a point source. A point source is usually produced by placing a pinhole before a lamp or other light source. Detecting a point source is the successful

determination of whether the source of light is present in the visual field. Detection does not require the observer to recognize (name), resolve (recognize as whole or sectioned), or localize (designate with a "position" response) any aspect of the point source.

The intensity or amount of energy required for visual system detection is determined by four major factors:

1. spatial layout

2. state of visual adaptation

3. exposure duration

4. wavelength

Hecht, Shlaer, and Pirenne (1942) attempted to control these conditions to determine a human's maximum sensitivity. They found that a minimum light intensity of 100 quanta was required for spot detection. Each of these characteristics plays a role in detection tasks.

Retinal locus. The receiver surface of the retina is extremely heterogeneous. In daylight conditions, maximum visual acuity is achieved when an image falls on the fovea. When the image falls only on the fovea, vision is referred to as central; otherwise it is lateral or peripheral. The location of a lateral projection is expressed by its eccentricity: the angle between the point of fixation and the center of the test object. Vision is parafoveal when the eccentricity is within 4-5 degrees, perifoveal between 4-5 and 9-10 degrees, and then peripheral.

Adaptation. On passing from strong sunlight into a darkened room, one has difficulty seeing until time passes and the eyes adapt to the state of lower illumination. In a relatively short time the intensity of light necessary for visual perception is noticeably decreased. The decrease in threshold with time in the dark is termed dark adaptation. A typical dark adaptation curve has one discontinuity that indicates the shift from day, or cone-dominated, vision to night, or rod-dominated, vision (Hecht, 1934). This 25- to 30-minute process for gaining fairly complete dark adaptation is progressively impaired with increasing oxygen deprivation (McFarland & Evans, 1939). The effects are thought to be caused by the influence of an oxygen deficiency on both the retina and the central nervous system.

The visual system changes when light levels change from the photopic range of 10^2 to 10^7 cd/m^2 to the scotopic range of 10^{-6} to 10^{-1} cd/m^2. Under scotopic (low light) conditions, the cones do not have sufficient sensitivity to function and, consequently, scotopic functioning depends almost exclusively on the more sensitive rod receptors. When the eye is fully dark adapted, the fovea is far less sensitive to stimulation than regions of the periphery (Hecht, Haig, & Wald, 1935).

Since the rod system is responsible for maximum sensitivity, location-specific variation to minimal amounts of light across the retina is primarily (though not entirely) determined by the density of the rods (Cornsweet, 1970). Spot detection sensitivity is greatest at about 10 degrees of eccentricity. Thus, when searching

for a point source of illumination in conditions of low

illumination, a person should look a bit to one side.

Stimulus integration. The retina sums quanta over both time

and space. Bloch's Law, dealing with the reciprocal temporal

relationship between the product of luminance at detection

threshold (L) and duration of stimulus (t), is expressed as

L times t is equal to a constant. This relationship holds for spot

flash durations up to 100 milliseconds for peripheral flashes

(scotopic conditions), and 10-20 milliseconds for foveal flashes

(photopic conditions).

The reciprocal space relationship between the area (A) of the

spot and the minimum luminance required for threshold detection (L)

is Ricco's Law: A times L is equal to a constant. When many rods

converge on a single ganglion cell, the activity level of that

optic nerve fiber is the same (barring inhibition) whether all the

light quanta are absorbed by a single rod or captured by many rods

that pool their stimulation. But if the stimulus quanta fall on an

area of rods larger than a single ganglion pool, then some of the

possible stimulation is lost to other ganglia, and detection

threshold may not be achieved.

Spectral sensitivity. Wavelength is an important factor

affecting the detection of a point source. The rod receptors for a

dark-adapted eye are unequally sensitive to different wavelengths

of light (Cornsweet, 1970). The spectral sensitivity function for

dark-adapted rod receptors (Wald, 1945) indicates that when

monochromatic light (light within a narrow range of wavelengths) is

presented to the eye, a 510 nm (green) stimulus requires the fewest quanta to be detected. The visual system sensitivity difference between 510 nm wavelength light and very long (red) or very short (blue) wavelengths is over a millionfold.

Resolution acuity threshold. Visual acuity is the capacity to discriminate the fine details of objects in the field of view. Measures of acuity test the resolving power of the eyes by determining the smallest spatial pattern or the smallest detail of a pattern that can be recognized as whole or sectioned. The spatial pattern in such tests is usually black on white. The contrast or difference in luminance between the black and white areas is typically made as great as possible.

In a visual acuity task, the size of the test pattern is reduced until its critical detail is no longer resolvable. This requires a frequency-of-seeing determination, and the threshold size is most commonly stated as the visual angle of the pattern detail that can be correctly detected 50 percent of the time. Visual acuity, or decimal acuity, is the reciprocal of the threshold when the latter is expressed in minutes of arc. Normal acuity, 1.0, is the ability to resolve a pattern whose critical dimension subtends 1 minute of arc.

Acuity tests. In aircrew physical examinations, as in most clinical applications, visual acuity is tested with either the Snellen Chart or the Landolt C test. The Snellen Chart contains rows of letters of the alphabet subtending decreasing visual angles. Invented by Snellen in 1862, it has since been

standardized by Sloan (1951). The Landolt C, or ring, is a broken circle with a stroke thickness and gap width one-fifth its outer diameter. Invented by Landolt in 1889, the rings have since been standardized by Shlaer (1937). A subject's resolving abilities have been confirmed once they discern 50 percent of the letters of one size on the Snellen Chart or correctly identify the orientation (direction of the gap opening) for 50 percent of the Landolt C's of a given size.

In 1956, Schade pioneered the use of spatial frequency as an experimental variable in grating detection and resolution tasks to assess visual performance. Each grating is a repeated sequence of light and dark bars. The width of one light bar and one dark bar of a grating is one cycle, or the period of the grating. The reciprocal of the period is the spatial frequency. Spatial frequency is expressed by the number of cycles of the grating that occur per degree of visual angle (cpd). Detection and resolution of a spatial frequency pattern are nearly synonymous; once a stripe pattern is detected, its fine detail or spatial pattern is recognized.

Ginsburg (1981) argues that the Snellen and Landolt standards assess only a small portion of an observer's true visual capabilities and limitations, because they are sensitive to only the highest spatial frequency range (resolving gaps of very small visual angle). Yet degradation in operator performance may occur from poor resolution (low contrast sensitivity) at lower spatial frequencies.

Variables affecting acuity. Acuity is affected by both target and observer variables (Westheimer, 1972). Target variables include retinal location, orientation, contrast, luminance, exposure duration, and wavelength. Observer variables include pupil size, degree of adaptation, and refractive error. The focusing abilities of aircrew members are tested as a part of their annual physical examinations. Military pilots who display marginally poor accommodation are fitted with corrective lenses and allowed to continue flight operations if normal accommodation can be restored with augmentation.

Acuity in a Landolt-ring vision task depends on both the luminance of the background on which the dark target is superposed and the contrast between the target and background. The relationship between intensity of illumination and acuity for Landolt rings was plotted by Shlaer (1937). Expressed logarithmically, acuity increases as a negatively accelerating function of log intensity. The curve has a discontinuity as intensity increases to the level at which the cone (photopic) detection threshold is exceeded. Maximum foveal acuity is maintained over a wide range of higher intensities (Brown, Graham, Leibowitz, & Ranken, 1953).

At higher levels of illumination (photopic conditions), acuity is maximized when the target is viewed with the center of the fovea. There is a significant drop in acuity when the image is displaced within the fovea (Miller, 1961) and a further decrease when the image is progressively displaced in the periphery. The

relationship between photopic acuity and stimulus eccentricity is generally consistent with cone concentration. However, there is evidence against such a similarly direct proportionality between scotopic acuity and rod concentration. When illumination is dim (scotopic conditions), acuity is highest for images located 4 degrees from the fovea, not 20 degrees where the greatest rod density exists (Mandelbaum & Sloan, 1947).

The size of the pupil affects resolution in two antagonistic ways. As the pupil increases in size, it improves acuity by both allowing more light to reach the retina and lessening edge diffraction. Yet, this larger opening lessens the sharpness of the resultant image on the retina due to geometric and chromatic aberrations and focus error caused by light rays passing through the lens progressively further from its center. Several investigators have shown that the best image is obtained with a pupil diameter between 2 and 4 mm (Campbell & Gubisch, 1966; Krauskopf, 1962; Westheimer & Campbell, 1962).

Among the various effects of the spectral composition of illumination, narrow bands of illumination produce the best minimum-visibilities and vernier acuities and reduce chromatic aberration (Baker, 1949; Shlaer, Smith, & Chase, 1942, respectively). However, Landolt-ring acuity shows no difference with narrow-band or wide-band illumination (Shlaer et al., 1942). When narrow bands are used in low-intensity illumination, wavelengths must be conditionally adjusted for photopic or scotopic sensitivity for acuities to be equal.

Another factor affecting night augmented focus is the NVG
itself. All imaging systems, whether real or virtual, cause eyes
to lapse toward their dark focus, or resting accommodation distance
(Hull, Gill & Roscoe, 1982; Randle, Roscoe, & Petitt, 1980; Roscoe,
in press). This shift causes both myopia, focusing too near, and
microposia, a decrease in apparent size. Each of these effects
would be expected to influence threshold detection slightly and
target resolution appreciably.

Hypoxia

When airmen or mountain climbers ascend to high altitudes,
changes take place in the environment that significantly influence
their performance and well-being. The most important feature of
high altitude is a reduction in barometric pressure. Air contains
oxygen along with nitrogen, carbon dioxide, and traces of rare
gases at a total pressure of 760 mm Hg at sea level. Each gas
exerts a partial pressure proportional to its volume. Table 1
shows that a reduction in the total barometric pressure with ascent
corresponds to a reduction in available oxygen (McFarland, 1953).

Physiological and psychological effects. The common term used
to refer to lack of oxygen is hypoxia. A reduction of available
oxygen results in a wide variety of physiological and psychological
effects dependent on the amount and duration of deprivation. In a
state of hypoxia the oxygen available to the cells is inadequate to
fulfill their energy requirements. Hypoxia can result from an
inability of the cells to use oxygen at a normal rate as well as
from insufficient delivery. A simplified classification of hypoxia

Table 1

Physical Characteristics of the Standard Atmosphere

| Altitude | Pressure | | Temp. | Equivalent | Partial Pressure |
feet	mm Hg	psi	deg C	Oxygen, %	of Oxygen, mm Hg
Sea Level	760.0	14.69	15	20.93	159.0
1,000	732.9	14.17	13	20.18	153.3
2,000	706.6	13.67	11	19.45	147.8
3,000	681.1	13.17	9	18.76	142.5
4,000	656.3	12.69	7	18.07	137.3
5,000	632.3	12.22	5	17.41	132.2
6,000	609.0	11.77	3	16.77	127.4
7,000	586.4	11.34	1	16.15	122.2
8,000	564.4	10.91	-1	15.54	118.1
9,000	543.2	10.50	-3	14.96	113.6
10,000	522.6	10.10	-5	14.39	109.3
11,000	502.6	9.72	-7	13.84	105.1
12,000	483.3	9.34	-9	13.31	101.1
13,000	464.5	8.98	-11	12.79	97.2
14,000	446.4	8.63	-13	12.29	93.4
15,000	428.8	8.29	-15	11.81	89.7
16,000	411.8	7.96	-17	11.34	86.1
17,000	395.3	7.64	-19	10.89	82.7
18,000	379.4	7.33	-21	10.45	79.4
19,000	364.0	7.03	-23	10.02	76.1
20,000	349.1	6.75	-25	9.61	73.0

is presented by Van Liere and Stickney (1963):

Anoxic — lack of oxygen in the arterial blood

Anemic — normal blood oxygen tension, but a shortage of functioning hemoglobin

Stagnant — normal oxygen content, but inadequate transfer to the tissues

Histotoxic — some cells are poisoned and unable to use oxygen

Hypoxia is characterized by an increase in rate and amplitude of respiration. According to Slonium (1974), the breathing increase is an almost immediate response to the decrease in arterial partial pressure of oxygen sensed by the carotid and aortic-body chemoreceptors. These compensatory mechanisms serve to counteract the effect of an oxygen deficit by more efficient activity of the cardiorespiratory system. Other physiological adjustments in response to acute hypoxia include the following:

- increased pulmonary ventilation, which increases alveolar partial pressure of oxygen and improves the oxygenation of blood flowing through the pulmonary capillaries

- increased cardiac output, caused mainly by increased heart rate

- selective redistribution of blood flow favoring the heart and brain

- increased ease of oxygen unloading in tissue capillaries from operation in the steep portion of the oxyhemoglobin dissociation curve.

Extended exposure at higher than normal habitation altitudes

results in increased production of red blood cells and automatic physiological effort to combat the lack of oxygen. However, this process occurs relatively slowly and cannot compensate for sudden extended exposures. As the degree and duration of hypoxia increase, the symptoms might progress as follows: headache, lack of attention, mental confusion, drowsiness, disturbance in vision, muscular weakness, and incapacitation (Slonium, 1974).

Human beings may survive through long periods of oxygen deficit if the degree of hypoxia is not too great. However, hypoxia still may cause marked behavioral changes. Barcroft found that beyond 15,000 feet (4,572 m) ASL, severe hypoxia often induces an alcoholic intoxication-like state of euphoria, self-satisfaction, and grossly distorted sense of reality (cited in Van Liere & Stickney, 1963). Both the short-term physiological and behavioral effects experienced at altitudes up to 20,000 feet (6,096 m) ASL are quickly reversed by breathing 100 percent oxygen.

Hypoxia causes drastic and easily recognizable deterioration in performance at altitudes close to the limit of human consciousness. A great deal of research has been directed to this topic, but the bias has been toward manual control tasks that treat the human operator as the physical manipulator of a mechanical system. Yet, it has been known for some time that certain predominantly mental tasks appear to be degraded by hypoxia at exposures to real and simulated altitudes below 10,000 feet (3,048 m) ASL.

Vision decrements. Of all the oxygen users in the body,
nervous tissue is the least capable of withstanding deprivation.
The brain requires a continuous supply of adequately oxygenated
blood to operate at peak efficiency. Billings (1973) indicated
that the brain and associated sensory apparatus (especially the
retina of the eye) have the highest oxygen uptake per unit mass of
any system of the body. While the nervous system accounts for
approximately 2 percent of body mass, it uses 20 percent of
inhaled oxygen at rest. Krause (1934) showed that because the
retina is anatomically a part of the brain, it likewise
functionally suffers from oxygen deprivation.

In a discussion of visual accommodation, Simonelli (1980)
suggests that visual performance is influenced by subtle
environmental conditions that affect the eye's accommodative
responses. Stressors such as sudden jolts and loud noises, as well
as elevated mental workloads, have been associated with an outward
shift in accommodation, while anesthesia and vestibular stimulation
are associated with an inward shift. The stress caused by hypoxia
would also be expected to bias accommodation, but evidently its
specific effects have not been measured and reported.

Fisher and Jongbloed (1935); Hecht, Shlaer, and Pirenne
(1942); McFarland (1937, 1938); and Wald (1942) have all shown that
hypoxia raises detection thresholds for both light- and dark-
adapted eyes. McFarland and associates (1939, 1940) reported a
decrease in visual sensitivity at a simulated altitude of only
7,400 feet (2,255 m) ASL; visual sensitivity and dark adaptation

were impaired at altitudes as low as 4,500 feet (1,371 m) ASL; and
at 12,000 feet (3,658 m) ASL there was a decline to 60 percent of
the sea-level visual acuity. Halperin, McFarland, Niven, and
Roughton (1959) noted that although exposure to altitudes between
7,000 feet (2,134 m) ASL and 20,000 feet (6,096 m) ASL changed
visual sensitivity these effects were reversed within a few
minutes by inhalation of 100 percent oxygen.

For any high-altitude task requiring resolution acuity, the
interaction between stimulus intensity and hypoxia is critical.
Although at higher illuminations there is little or no impairment
in vision at altitudes below 18,000 feet (5,486 m) ASL, under
reduced illumination, a decrease in the ability to resolve a given
target has been found as low as 8,000 feet (2,438 m) ASL (McFarland
& Halperin, 1940).

The Army and MAC Rescue Services are both aware of the effects
of hypoxia on mission performance and safety. In addition to
extensive initial and periodic refresher training in hypoxia
symptom recognition, both services have published regulations aimed
at lessening aircrew exposure to hypoxic conditions. Neither
service allows its aviators to fly aircraft above 13,000 feet
(3,962 m) ASL without supplemental oxygen. Flight between 10,000
feet (3,048 m) and 13,000 feet (3,962 m) ASL is limited to one
hour, without special waiver, if supplemental oxygen is not
available and used.

Military flying organizations recognize the need for
guidelines to lessen hypoxic exposure, but with their subsequent

incorporation of NVGs, none has investigated how hypoxia might influence NVG-augmented perception or entertained changes in their regulations concerning use of supplemental oxygen. The evidence concerning hypoxia has persuaded Billings (1973) to conclude that hypoxic conditions are less pronounced at lower altitudes, but they exist and may be important under certain circumstances. The importance of the low-level hypoxic environment and NVG-augmented night vision motivated this scientific investigation.

Inducing hypoxia. The effects of hypoxia can be investigated in natural high-altitide field conditions or with any of the following artificial laboratory methods:

- use of a rebreather
- use of a low-pressure chamber
- dilution of air or oxygen by some inert gas such as nitrogen or helium
- artifical pneumothorax
- artifical resriction of the free influx of atmosphere into the lungs (induced blood chemistry imbalance or extraction/dilution of blood cells).

For studies using human subjects, any of the first three techniques is acceptable, but the third is the least expensive and best suited for accurate altitude adjustment when a low-pressure chamber is not readily available. This dilution-of-air method of oxygen deprivation was initially used by Dreyer (1920) but today is far easier and more precise through the development and use of tight-fitting masks, flow regulators, and extremely accurate

gaseous mixtures. Simulation of atmospheric conditions within 20 feet (6 meters) of desired altitude is currently possible.

Method

Apparatus

The experimental apparatus consisted of three major components: the NVGs (AN/PVS-5), the oxygen-metering apparatus used for altitude simulation, and the vision-task apparatus. The NVGs have been previously addressed. They were loaned for this experiment by the 1550th Combat Crew Training Wing (CCTW), Kirtland Air Force Base, New Mexico. The other two items were fabricated.

Oxygen-metering apparatus. Parts for the oxygen apparatus were procured from the Arizona Medical Supply Company, Inc., Albuquerque, New Mexico and the Kirtland Air Force Base Hospital. The equipment and gas requirements were as follows:

1 Foregger, facemask, 651105, adult

1 Foregger, headstrap, 751004

1 Foregger, mask elbow, 701066

1 Foregger, non-rebreathing valve, 701055

1 Foregger, breathing bag, 503102, 2 liter

5 Puritan, regulators, 128314, 0-8 LPM

6 Inspiron, prefilled humidifiers

1 Size E Cylinder, 25.48% oxygen in a balance of nitrogen

1 Size E Cylinder, 19.58% oxygen in a balance of nitrogen

1 Size E Cylinder, 17.52% oxygen in a balance of nitrogen

1 Size E Cylinder, 15.58% oxygen in a balance of nitrogen

1 Size H Cylinder, 100% oxygen

1 Size H Cylinder, 100% nitrogen

1 Oxygen Analyzer, in-line

The E-cylinder gases were mixed to certified grade, and their analyzed oxygen content was confirmed accurate to within 0.05 percent. When gas was mixed upon delivery, a cardiopulmonary technician confirmed oxygen content accuracy to within 0.2 percent. No subsequent altitude interpolation was deemed necessary as 0.05 percent and 0.2 percent variance in oxygen concentration equates to approximately 77 feet (23 m) and 300 ft (91 m), respectively. The oxygen percentages were adjusted from standard altitude conditions (Table 1) to compensate for delivery at Kirtland Air Force Base, Albuquerque, New Mexico, situated 5,350 feet (1,630 m) ASL.

Vision-task apparatus. The vision tester presented square-wave gratings at varying levels of illumination. One of its components, a calibrated circular neutral density filter, was manually rotated by the experimenter and its position recorded when detection of the square-wave grating pattern was correctly reported. The vision apparatus is shown in Figure 3, and each component is named and its function addressed.
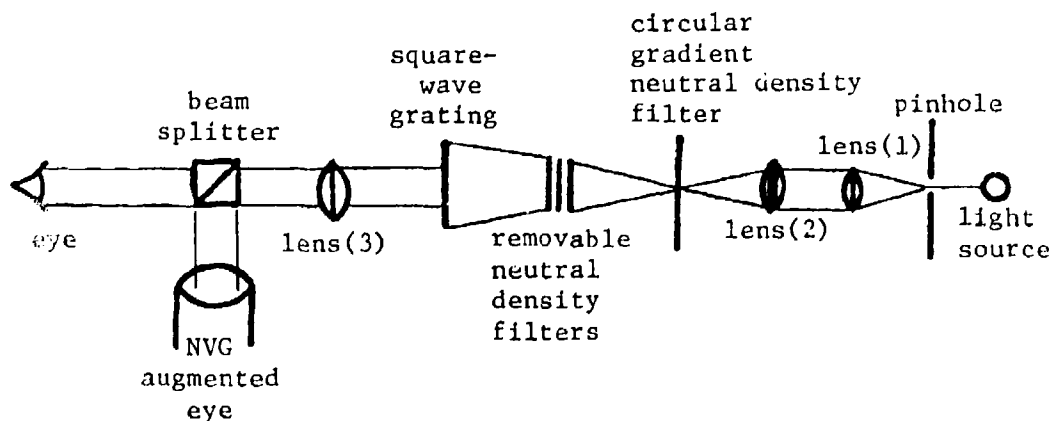
Figure 3. Vision testing apparatus.

Light source: The bandwidth of the 25 watt bulb used as the light source included 450 nm to 820 nm and had an unfiltered luminance of 110 foot-lamberts (3.77 x 10 cd/m^2). The spectral characteristics of the light source (Figure 4) were confirmed with a computer controlled monochromator detector wheel and radiometer testing apparatus.

Pinhole: This shield redefined the light source and prevented all source light from serving as target illumination except that passing through its 3-mm center hole.

Lens (1): A plano-convex spherical glass lens was positioned one focal length from the pinhole, thereby collimating the source light.

Lens (2): A precision-optimized spherical achromatic lens with a focal length of 100-mm was positioned to focus the light in
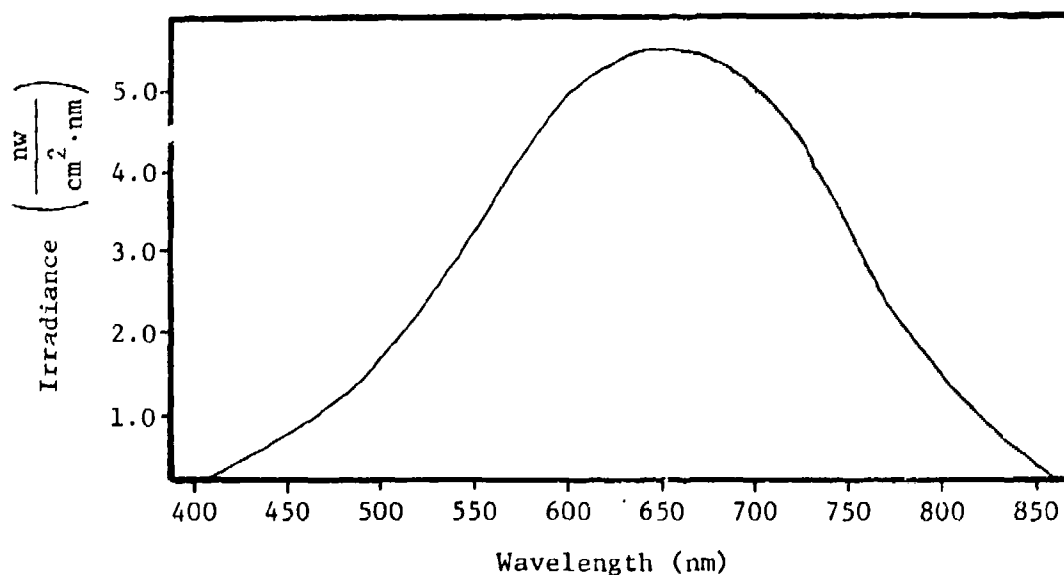

Figure 4. Light source spectral composition.

the center of the circular-gradient neutral-density filter
aperture.

Light-tight circular-gradient neutral-density filter (Oriel
Corporation, Model Number 2868): A calibrated dial attached
externally to the gradient filter indicated the density in the
center of the filter's 0.5-inch aperture and allowed precise and
repeatable control of density variance. As the light-tight
enclosed disc was rotated 285 degrees, density ranged from 0.2 to
2.0 log unit filtration.

Removable neutral-density filter: Fused-silica-substrate
metallic neutral-density filters provided a gross reduction in
illumination intensity without spectral change during low-level
(NVG augmented) testing and upon removal, a higher illumination
level for nonaugmented testing. Filters with densities of 3.0,
1.0 (two) and 0.5 allowed 0.1, 10.0, and 31.6 percent source-light-
transmission, respectively.

Square-wave grating: Four singularly interchangeable square-
wave grating slides provided targets of 14, 7, 3 1/2 and 1 3/4 cpd
with either a vertical or horizontal orientation.

Lens (3): A 100-mm precision-optimized spherical achromatic
lens was positioned one focal length from the eye at either
observation point.

Beam splitter: A 40-mm cube beam-splitting prism reflected
50 percent of the light and passed the remainder.

Unaugmented eye position: The observer's eye was positioned
one focal length from the achromatic lens; the forehead and face

were pressed against a secured NVG housing structure identical to that in the NVG viewing position; however, there were no optics or obstructions to interfere with the subject's vision from this position. The grating subtended twenty degrees of the visual field. With the 1 3/4 cpd grating slide in place, an illuminance of 4 cd/m^2 at this naked-eye viewing position was measured with a photometer.

NVG-augmented eye position: The grating seen through the goggles appeared the same size as in the unaugmented position, subtending twenty degrees of the visual field. A post-NVG-amplified illuminance of 75 cd/m^2 was measured at this viewing position by the same photometer.

Observers

Six male United States Air Force pilots participated in this study. They were volunteers from personnel assigned to the 1550th CCTW, Kirtland Air Force Base, New Mexico. Prior to participation each observer's most recent annual flight physical examination was reviewed by a Kirtland AFB Flight Surgeon to confirm normal uncorrected vision. Each participant had flown with the NVGs and was familiar with their normal operation. Written permission was received from the Air Force Office of the Surgeon General to conduct this investigation with Air Force personnel at an Air Force installation.

Experimental Design

This study of the effect of hypoxia on NVG-augmented detection/resolution threshold entailed a 2 x 4 x 4 factorial

design. Observers performed square-wave grating resolution tasks both with and without NVGs under four simulated altitude conditions. The four simulated altitudes were sea level, 7,000 feet (2,134 m) ASL, 10,000 feet (3,048 m) ASL, and 13,000 feet (3,963 m) ASL. The square-wave gratings presented the four following frequencies: 14 cpd, 7 cpd, 3 1/2 cpd, and 1 3/4 cpd. In addition, the effects of a brief exposure to 100 percent oxygen were tested after performance at each of the four simulated altitudes.

Procedures

Four of the observers participated in four 70-minute testing sessions conducted over four consecutive days. Each testing session began with the observer seated in a room with the experimenter and apparatus. The room was darkened once the observer's left eye was patched and the observer dark-adapted for 15 minutes. While still in darkness, the observer then breathed from one of the gaseous mixtures for an additional 15 minutes. The mixture was different for each of the four days, and the order of presentation was varied across observers, as shown in Table 2. During the 30-minute dark-adaptation/hypoxic-initiation period, the testing procedures were reviewed. The gas mixture was breathed throughout the experiment and changed to 100 percent oxygen for the final two tasks.

After dark adaptation, the observer was positioned at the non-NVG viewing station. The illumination of each of the four square-wave grating frequencies was individually increased until its

Table 2

Simulated-Altitude Testing Order

Subject 1 -	10,000 ft	7,000 ft	13,000 ft	Sea Level
Subject 2 -	7,000 ft	Sea Level	10,000 ft	13,000 ft
Subject 3 -	Sea Level	13,000 ft	7,000 ft	10,000 ft
Subject 4 -	13,000 ft	10,000 ft	Sea Level	7,000 ft
Subject 5 -	Sea Level	7,000 ft	10,000 ft	13,000 ft
Subject 6 -	13,000 ft	10,000 ft	7,000 ft	Sea Level

vertical or horizontal orientation was correctly identified twice. Pretesting revealed no significant difference in variance for four, three, or two consecutive observations. The presentation order of the gratings was varied as shown in Table 3. The first grating

Table 3

Square-Wave Grating Presentation Order

Subject 1 -	1.75 cpd	3.50 cpd	7.00 cpd	14.00 cpd
Subject 2 -	3.50 cpd	7.00 cpd	14.00 cpd	1.75 cpd
Subject 3 -	7.00 cpd	14.00 cpd	1.75 cpd	3.50 cpd
Subject 4 -	14.00 cpd	1.75 cpd	3.50 cpd	7.00 cpd
Subject 5 -	14.00 cpd	7.00 cpd	3.50 cpd	1.75 cpd
Subject 6 -	1.75 cpd	3.50 cpd	7.00 cpd	14.00 cpd

each subject viewed was tested once more after each of the four was individually presented. This allowed a quantitative examination of performance decrement attributable to repeated light exposure and possible change in degree of dark adapatation.

The observer then moved to the NVG-augmented viewing station. Grating detection tasks were reaccomplished in the same manner and with the same subject-specific grating presentation orders as used at the non-NVG station. The observer's gas mixture was then changed to 100 percent oxygen. After three minutes, the same tasks were repeated at each viewing station with continuous delivery of 100 percent oxygen. Thirty-four observations were recorded during each test session as shown in Figure 5.
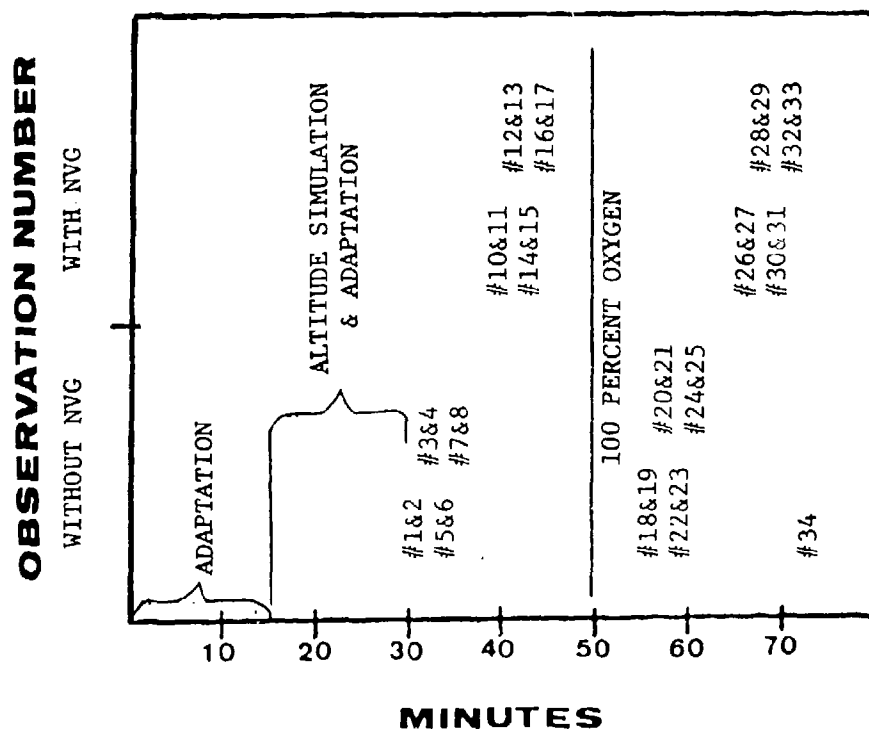

Figure 5. Single-session data gathering.

Depletion of premixed gas required on-site gas mixing for two additional subjects (subjects 5 and 6 in Table 2 and Table 3). An in-line oxygen analyzer was used to monitor mixture balance continuously. The need for cardiopulmonary technician support required that each of these individuals be tested for all altitudes in a single session. Thus, the final two subjects performed the same grating resolution tasks consecutively, e.g.: dark-adaptation/oxygen-deprivation to one test altitude, non-augmented and NVG observations; dark-adaptation/oxygen-deprivation to the second test altitude, non-augmented and NVG observations; dark-adaptation/oxygen-deprivation to the third test altitude, non-augmented and NVG observations; etc. One subject was tested in an ascending altitude order, the other in a descending order. Following their final test altitudes, each subject was delivered 100 percent oxygen and tested once in the same manner as the first four subjects.

Performance Measurement

Both the distance of the luminous source and the inclination of the surface with respect to its direction were kept constant in this investigation. The remaining influence on illumination, the intensity of the light source, was the dependent experimental variable. Changing the light output at its source, however, would have affected its wavelength composition. Thus, the illuminance of the target gratings was controlled through filtering. In this case, neutral density filters allowed a uniform attenuation of light across the spectrum of interest.

Neutral density filters have specified optical densities.

Their transmission percentage is the proportion of light they allow to pass, e.g., a filter that allows 10 percent transmission is referred to as a 1.0 log filter and a filter that allows 1 percent transmission as a 2.0 log filter. In this study, the illuminance of the grating was calculated by recording the density of filtration between the source and the observer. This log scale was retained for performance analysis. Thus, a high log sensitivity performance score means that a subject could resolve a grating orientation with a large amount of filtration; he needed less light for target resolution.

Results

The influence of the modification in the method of altitude
simulation and in experimental procedure on visual performance for
subjects 5 and 6 could not be assumed to be insignificant, so the
data were first analyzed separately for subjects 1-4 and 5-6.
There were no major inconsistencies; however, only data from the
balanced design with subjects 1-4 who were tested at a single
simulated altitude on each of four separate occasions will be
reported and discussed.

Figure 6 shows the mean log sensitivity plots both with and
without NVG augmentation. A repeated measures analysis of variance
was performed on the log sensitivity data. With no supplemental
oxygen, there were two highly and one marginally significant main
effects: performance deteriorated with increasing grating spatial
frequency, $F(3,256) = 856.90$, $p < 0.0001$; improved with NVG
augmentation, $F(1,256) = 249.36$, $p < 0.0001$; and tended to
deteriorate with increasing altitude, $F(3,256) = 2.24$, $p < 0.080$.
(When data from all six subjects was pooled and analyzed, the
altitude main effect was also significant, $F(3,288) = 3.3$,
$p < 0.02$.) The only significant interaction was between spatial
frequency and NVG augmentation, $F(3,256) = 142.53$, $p < 0.0001$.

Linear model analysis of performance without supplemental
oxygen revealed that with no augmentation none of the four altitude-
specific sensitivity plots differs significantly in slope, but the
lowest and highest altitude lines are sufficiently displaced to
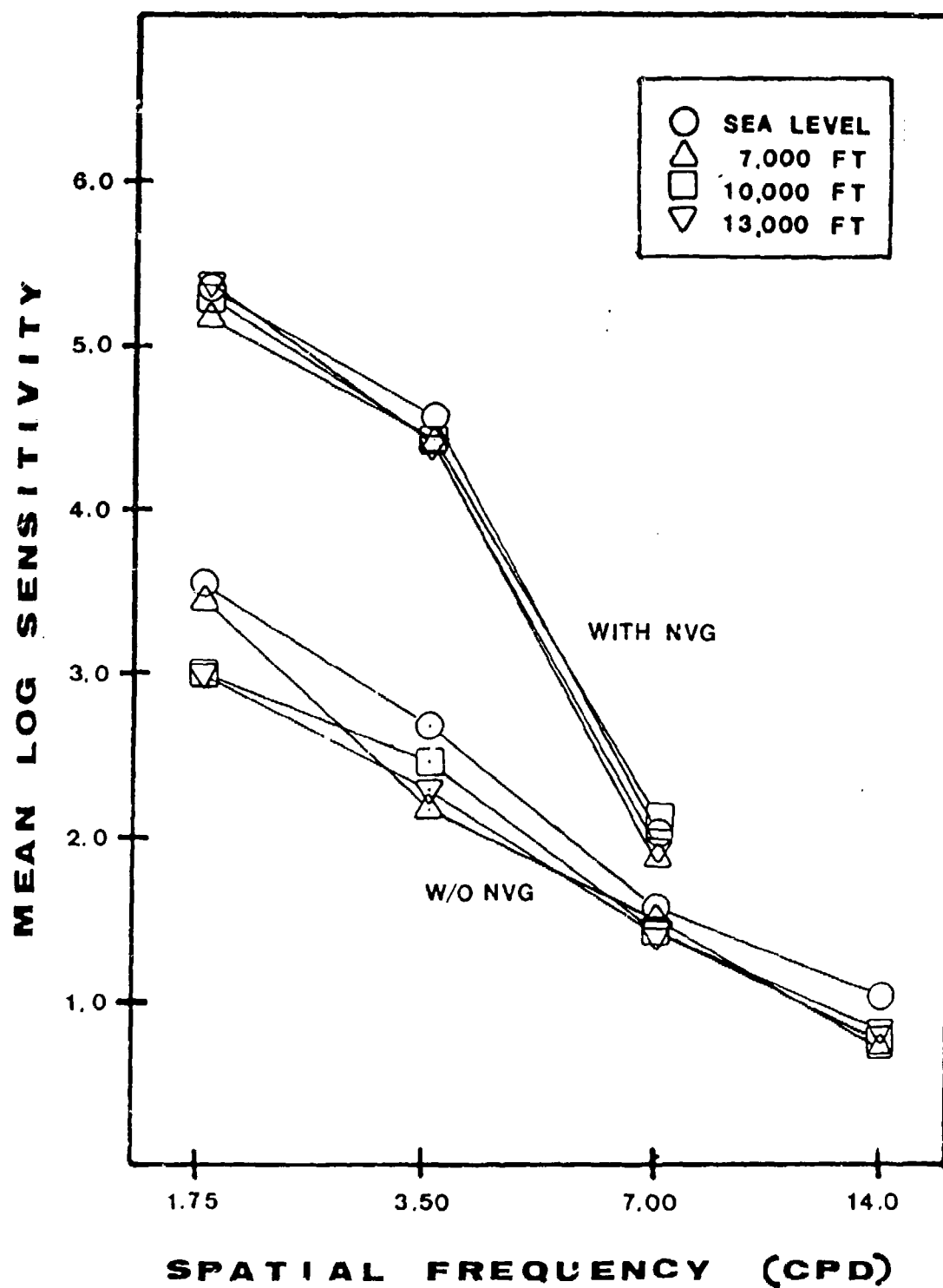make them significantly different from each other, $t(126) = 2.16$,

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Figure 6. Performance without supplemental oxygen.

$p < 0.05$. This is consistent with the overall analysis of variance that shows the effect of altitude to be marginally significant. However, with NVG augmentation there is no significant difference among the slopes or positions of the four altitude-specific plots.

When supplemental oxygen was delivered after hypoxic exposure, there were two significant main effects: performance deteriorated with increasing grating spatial frequency, $F(3,256) = 993.96$, $p < 0.0001$; and improved with NVG augmentation, $F(1,256) = 188.89$, $p < 0.0001$. The only significant interaction was between spatial frequency and NVG augmentation, $F(3,256) = 176.86$, $p < 0.0001$.

Figure 7 shows the mean log sensitivity plots both with and without NVG augmentation after subjects received 100 percent oxygen for three minutes subsequent to an altitude simulation. Performance with NVG augmentation for the 14 cpd grating was not measurable because even with full unfiltered illumination no subject resolved the grating orientation. Linear model analysis revealed that without NVGs, none of the four sensitivity plots following altitude simulation has a significantly different slope, but the second lowest (7,000-foot) and highest (13,000-foot) altitude lines are sufficiently displaced to make them different from each other, $t(94) = 2.13$, $p < 0.05$. Again, with NVG augmentation there is no difference among the slopes or displacements of the altitude-specific post-test plots.

Figure 8 shows performance means as a function of time. The balanced nature of the experimental design allows such subject integration. Comparison of pre- and post--100-percent-oxygen
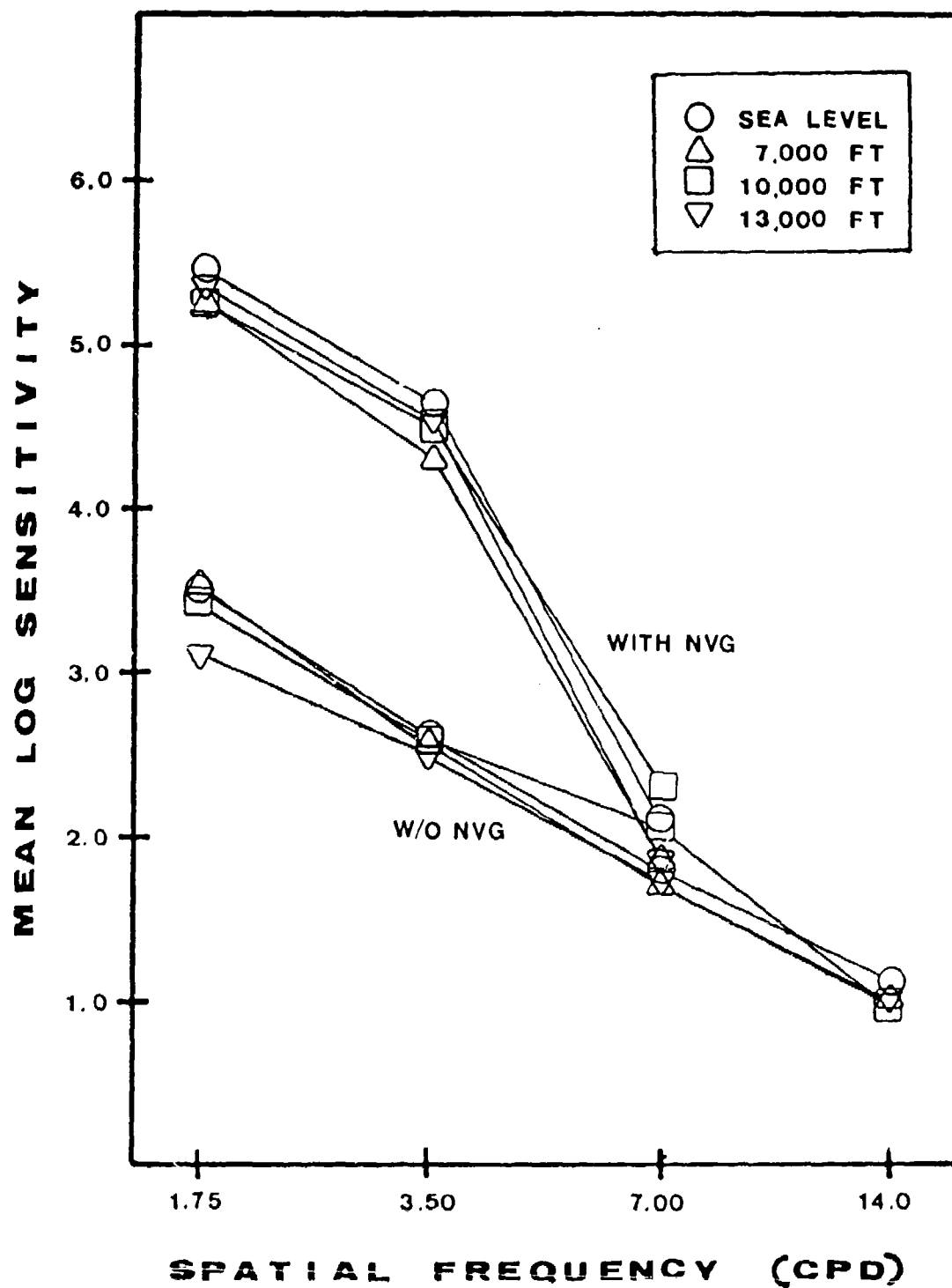
Figure 7. Performance with supplemental oxygen following test altitudes.

performance reveals a difference of 0.19 log sensitivity (2.03

versus 2.22) between naked-eye oxygen-deprived and oxygen-

supplemented performance. However, a difference of only 0.02 log

sensitivity (3.93 versus 3.95) is observed between NVG-augmented

oxygen-deprived and oxygen-supplemented performance.

Finally, a direct altitude-specific comparison was made across

subjects and gratings for each of the four testing sessions. Each

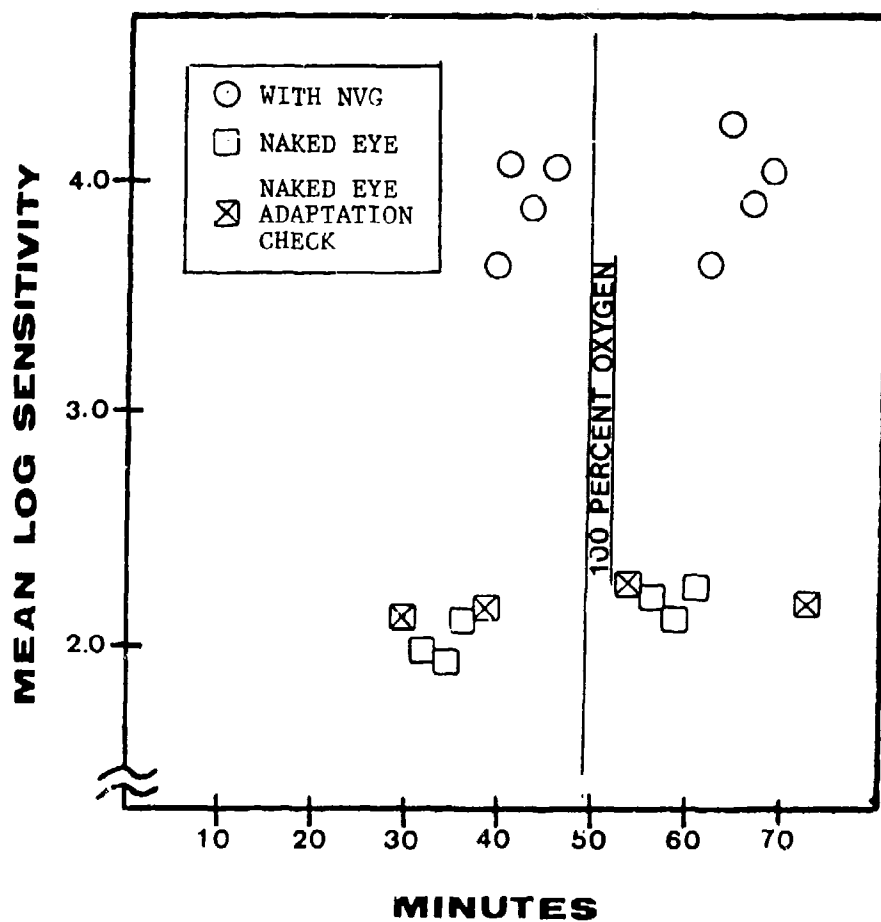subject's 1st and 2nd observations (Figure 5) were averaged and

Figure 8. Performance means.

compared to his averaged 18th and 19th observations, 3rd and 4th to
20th and 21st, 5th and 6th to 22nd and 23rd, etc. The results are
shown in Table 4. In 52 of 64 cases, less illumination was
required for oxygen-supplemented naked-eye resolution.

When examined by altitude, incidence of performance
improvement logically increased with ascent; 69 percent of the

Table 4

Changes In Mean Illumination Levels Required For Resolution After
Supplemental Oxygen.

	Without NVG				
	Sea level	7,000	10,000	13,000	Total
Less illumination	11	13	14	14	52
No change	0	1	0	1	2
More illumination	5	2	2	1	10
	With NVG				
	Sea level	7,000	10,000	13,000	Total
Less illumination	6	6	5	5	22
No change	1	0	3	0	4
More illumination	5	6	4	7	22

Note: There are 12 trials for NVG viewing at each altitude rather than
16 because the 14 cpd gratings could never be resolved with the NVGs.

sea-level post-oxygen resolutions were made with less illumination
than in the unsupplemented sea-level condition, whereas 88 percent
of the 13,000-foot post-oxygen resolutions were made with less
illumination than in the preceding 13,000-foot oxygen-deprived
condition. In contrast, no such post-oxygen improvement is evident
with NVG augmentation; with supplemental oxygen there was an equal
likelihood that resolutions required more or less illumination.

Discussion

Hypoxia differentially affected unaided and aided performance, as evident from both the graphic plots shown in Figures 6 and 8 and from the various statistical effects. Overall, the lack of oxygen significantly degraded unaided but not NVG-augmented performance. As shown in Figure 9, the naked-eye tests were done in scotopic, rod-dominant conditions. Only with the two higher-frequency gratings did illuminance levels required for resolution approach a mesopic condition. In contrast, the NVGs provided an amplification
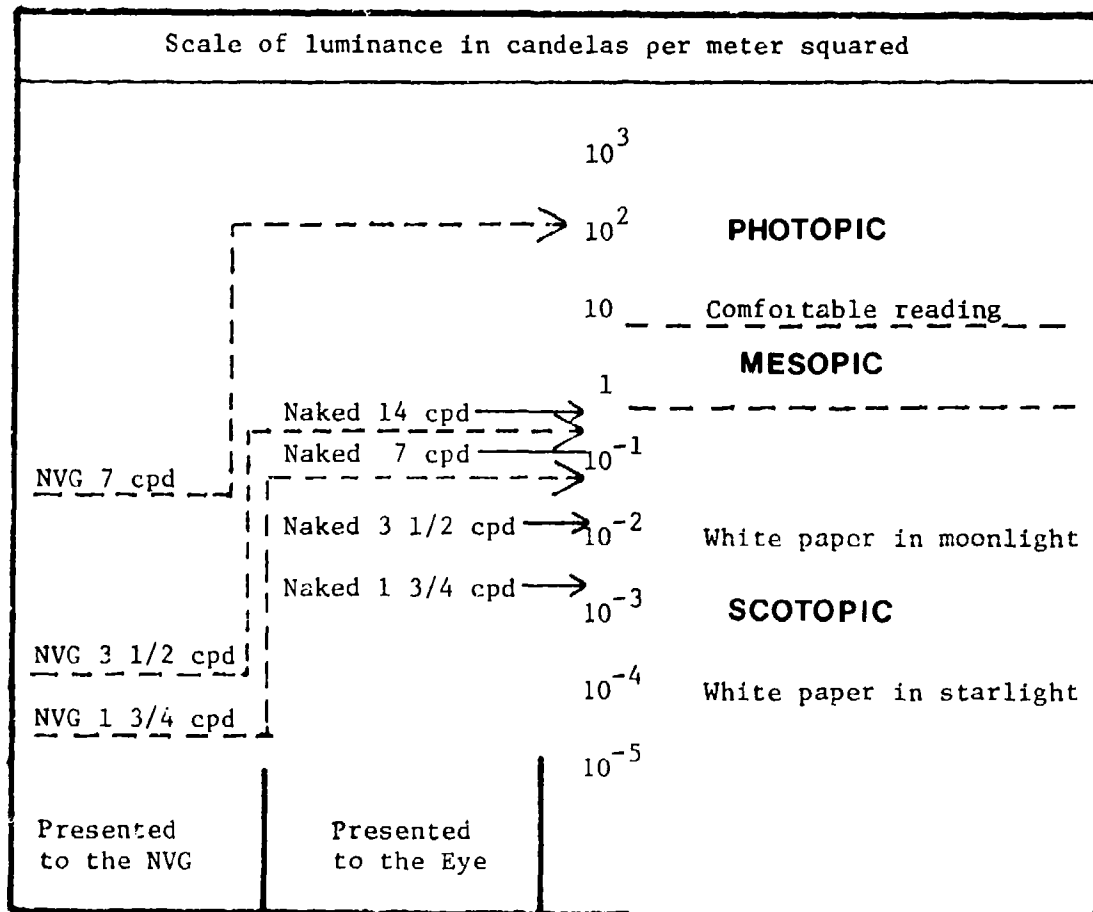

Figure 9. Square-wave grating mean luminance levels.

of illuminance and boosted two of the three NVG-augmented scotopic levels to photopic and borderline mesopic values.

Grating resolution performance was also differentially affected by hypoxia with and without augmentation. In neither the unaugmented nor the NVG condition was there an altitude-by-grating interaction; however, the significant goggle-by-grating interaction is evident in Figures 6 and 7. The slope of the increase in illumination required with the NVGs for resolution with increasing spatial frequencies was 50 percent steeper than that for unaided vision. The overall increase in required illumination associated with increasing spatial frequency, shown in Figure 9, is consistent with McFarland's (1953) findings.

The reasons higher spatial frequencies require more illumination are twofold. First, rods have lower resolving power than cones. In low illumination, there is less light to stimulate the rods, and no help from the cones is available until the illumination is in a mesopic range. Second, when the pupil opens in low illumination, target definition suffers, thereby requiring more light or targets of lower spatial frequencies for resolution. A grating-frequency main effect has been found in most low-level illumination studies that likewise show increasing deterioration with higher spatial frequencies (Campbell & Green, 1965).

Figure 9 shows that the NVGs presented to the observer a grating with 100 to 1000 times the average illuminance of the filtered source. Of particular note is the fact that when the square-wave grating frequency was 7 cpd, performance with the

goggles was only slightly (though consistently) better than without augmentation. This shows the tradeoff involved in goggle augmentation; the NVGs degrade resolution, but this is more than counterbalanced by the increase in illumination. However, with the 14 cpd square-wave grating, the illumination amplification could not make up for the resolution lost in image processing. When the 14 cpd grating was presented, the observers reported only a very bright field; none resolved the grating.

Naked-eye performance improved with supplemental oxygen. Table 4 shows that with 100 percent oxygen there was a consistent improvement over any simulated altitude condition. As in many of the previously cited vision investigations, the oxygen requirements of the visual sensory system are sufficiently high that even slight deficiencies result in performance degradation. But with the frequencies tested in this experiment, NVG-augmented performance did not suffer in oxygen-deprived environments up to 13,000 feet (3,963 m) ASL.

The maintance of dark adaptation was checked in this experiment. Figure 8 graphically shows that dark adaptation was not compromised during unaugmented testing; the ratio of instances requiring more illumination versus less illumination on 9th trials versus 1st trials across sessions was 9 to 7. However, there was adaptation loss from NVG-augmented viewing; more illumination was required for naked-eye resolution in 11 of 16 post-oxygen-supplemented NVG observations.

Lastly, the subject's habituation to Kirtland AFB,

Albuquerque, New Mexico, (5,350 feet ASL) might influence

generalization to those not so acclimatized. The effect of hypoxia

on resolution performance observed in this experiment may

underestimate the hypoxic vision decrement of observers

acclimatized to sea level.

Conclusions

This experiment answered three questions of interest to NVG users. The visual environment produced by NVG augmentation does not seem to necessitate adjustments in flight restrictions or search procedures other than consideration of target size. Moderate hypoxia did not significantly affect the NVG-augmented square-wave grating resolution acuity of observers acclimitized to 5,350 feet (1,630 m) ASL. Up to 13,000 feet (3,962 m) ASL there was no significant degradition in target resolution performance. Without augmentation, however, there was a significant difference between resolution performance at sea level and at 13,000 feet (3,962 m) ASL. The latter altitude necessitated a significantly higher target illumination.

In both aided and unaided conditions the illumination needed to resolve the target was influenced by its spatial frequency; higher frequency targets required higher illumination. However, the NVG's overall performance superiority was limited to spatial frequencies of 7 cpd and below. In no case was a subject able to resolve a 14 cpd target with the NVGs. As a result the naked-eye acuity at the highest spatial frequency tested was superior to that with augmented illumination but reduced resolution.

Finally, there was consistent improvement in unaided resolution performance after a three-minute exposure to 100 percent oxygen over any of the simulated altitude conditions. The degree of improvement logically increased with ascent. However, supplemental oxygen did not consistently improve NVG-augmented

performance. With supplemental oxygen, there were equal occurrences of performance improvement and deterioration.

Most importantly, this study revealed no hypoxic performance decrement up to 13,000 feet (3,962 m) ASL with NVG augmentation. The investigation shows no reason to revise current flying or search altitudes directives. The likelihood that oxygen supplementation would improve NVG-aided resolution acuity up to 13,000 feet (3,962 m) ASL is not indicated by this study.

REFERENCES

Baker, K. E. (1949). Some variables influencing vernier acuity: I. Illumination and exposure time, II. Wavelength of illumination. Journal of the Optical Society of America, 39, 567-576.

Billings, C. E. (1973). Atmosphere. In J. F. Parker, Jr. & V. R. West (Eds.), Bioastronautics data book (Scientific Paper NASA-SP-3006, pp 35-63). Washington DC: National Aeronautics and Space Administration.

Bouman, M. A. & van der Velden, H. A. (1947). The two-quanta explanation of the dependence of the threshold values and visual acuity on the visual angle and the time of observation. Journal of the Optometric Society of America, 37, 908-919.

Brown, J. L., Graham, C. H., Leibowitz, H. & Ranken, H. B. (1953). Luminance thresholds for the resolution of fine detail during dark adaptation. Journal of the Optometric Society of America, 43, 197-202.

Campbell, F., & Green, D. (1965). Optical and retinal factors affecting visual resolution. Journal of Physiology, 181, 576-593.

Campbell, F. W. & Gubisch, R. W. (1966). Optical quality of the human eye. Journal of Physiology, 186, 558-578.

Cornsweet, T. N. (1970). Visual perception. New York: Academic Press.

Davson, H. (1962). The Eye (Vol. 2). New York: Academic Press.

Dreyer, G. (1920). Britain Privy Council, Medical Research Council, Special Report Service (No. 53, p. 10).

Fisher, F. P. & Jongbloed, J. (1935). Archive augenh, 109, 452.

Ginsburg, A. P. (1981). Proposed new vision standards for the 1980's and beyond: Contrast sensitivity (Technical Paper AFAMRL-TR-80-121). Wright-Patterson Air Force Base, Ohio: USAF Aerospace Medical Research Laboratory.

Goldman, H. & Schubert, G. (1933). Archive Augenh, 107, 216.

Halperin, M. H., McFarland, R. A., Niven, J. I., & Roughten, A. (1959). The time course effects of carbon monoxide on visual threshold. Journal of Physiology, London, 146, 583-593.

Hecht, S. (1934). Vision: II. The nature of the photoreceptor process. In C. Murchinson (Ed.), A handbook of general experimental psychology. Worcester: Clark University Press.

Hecht, S., Haig, C., & Wald, C. (1935). The dark adaptation of retinal fields of different size and location. Journal of General Physiology, 19, 321-339.

Hecht, S., Shlaer, S., & Pirenne, M. H. (1942). Energy, quanta, and vision. Journal of General Physiology, 25, 819-840.

Hull, J. C., Gill, R. T., & Roscoe, S. N. (1982). Locus of the stimulus to visual accommodation: Where in the world, or where in the eye? Human Factors, 24, 311-319.

Jensen, R. S. (1981). First symposium on aviation psychology. Columbus, OH: The Ohio State University, Aviation Psychology Laboratory.

Krause, A. C. (1934). The biochemistry of the eye. Baltimore: Johns Hopkins Press.

Krauskopf, J. (1962). Light distribution in human retinal images. Journal of the Optical Society of America, 52, 1046-1050.

Mandelbaum, J. & Sloan, L. L. (1947). Peripheral visual acuity. American Journal of Ophthalmology, 30, 581-588.

McFarland, R. A. (1937). Psycho-physiological studies at high altitude in the Andes. Journal of Comparative Psychology, 23, 191-225.

McFarland, R. A. (1938). The effects of oxygen deprivation (high altitude) on the human organism (Report No. 13). Washington DC: US Department of Commerce, Bureau of Air Commerce.

McFarland, R. A. (1953). Human factors in air transportation. New York: McGraw-Hill.

McFarland, R. A. & Evans, J. N. (1939). Alterations in dark adaptation under reduced oxygen tensions. American Journal of Physiology, 127, 37-50.

McFarland, R. A. & Halperin, M. H. (1940). The relation between foveal visual acuity and illumination under reduced oxygen tension. Journal of General Physiology, 23, 613-630.

Miller, N. D. (1961). Variation of resolving power of the retina with distance from the fovea center. Journal of the Optical Society of America, 51, 1462.

Randle, R. J, Roscoe, S. N., & Petitt, J. (1980). Effects of accommodation and magnification on aimpoint estimation in a simulated landing task (Technical Paper NASA-TP-1635). Washington, DC: National Aeronautics and Space Administration.

Roscoe, S. N. (in press). Judgements of size and distance with imaging displays. Human Factors.

Schade, O. H. (1956). Optical and photoelectric analog of the eye.

Journal of the Optical Society of America, 46, 721-739.

Shlaer, S. (1937). The relation between visual acuity and illumination. *Journal of General Physiology*, 21, 165-188.

Shlaer, S., Smith, E. C., and Chase, A. M. (1^42). Visual acuity and illumination in different spectral regions. *Journal of General Physiology*, 25, 553-569.

Simonelli, N. M. (1980). The dark focus of accommodation: Its existence, its measurement, its effects. (Doctoral dissertation, University of Illinois at Urbana-Champaign, 1980). *Dissertation Abstracts International*, 41(02B), 722. (University Microfilms No. 80-17984; also issued in 1979 as Technical Report BEL-79-3/AFOSR-79-7. Las Cruces, NM: New Mexico State University, Behavioral Engineering Laboratory.)

Sloan, L. L. (1951). Measurement of visual acuity. *Archives of Ophthalmology*, 45, 704-755.

Slonium, N. B. (Ed.). (1974). *Environmental physiology*. St. Louis: Mosby.

Van Liere, E. J. & Stickney, J. C. (1963). *Hypoxia*. Chicago: University of Chicago Press.

Wald, G. (1942). Respiratory effects upon the visual threshold. *Journal of General Physiology*, 25, 891-902.

Wald, G. (1945). Human vision and the spectrum. *Science*, 101, 653-658.

Westheimer, G. (1972). Visual acuity and spatial modulation thresholds. In D. Jameson & L. M. Hurvich (Eds.), *Handbook of sensory physiology: Visual psychophysics* (Vol. VII/4). Berlin:

Springer-Verlag.

Westheimer, G. & Campbell, F. W. (1962). Light distribution in the
image formed by the living human eye. Journal of the Optical
Society of America, 52, 1040-1044.